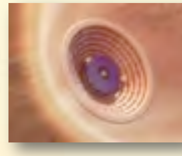
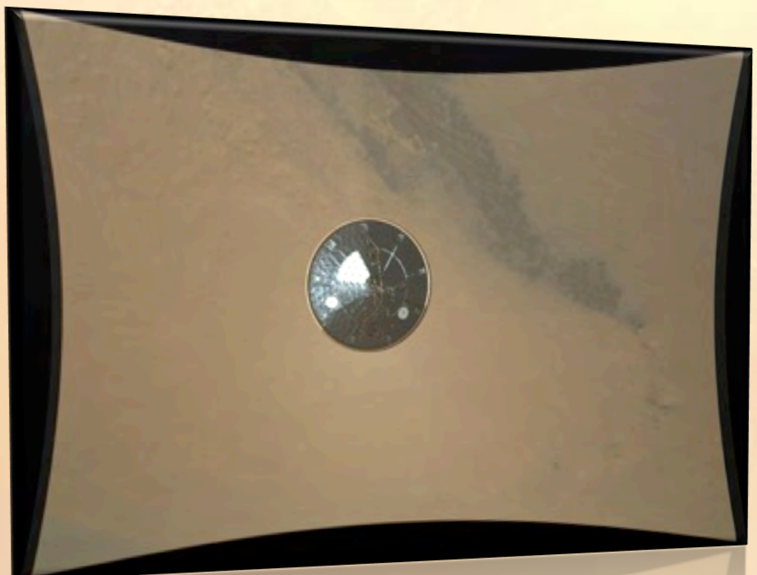
Space Technology Program
Recent Successes



MSL Entry, Descent, and Landing Instrumentation (MEDLI)



Inflatable Reentry Vehicle Experiment 3 (IRVE-3)

Briefing for
NASA Advisory Council
Technology and Innovation Committee

November 15, 2012

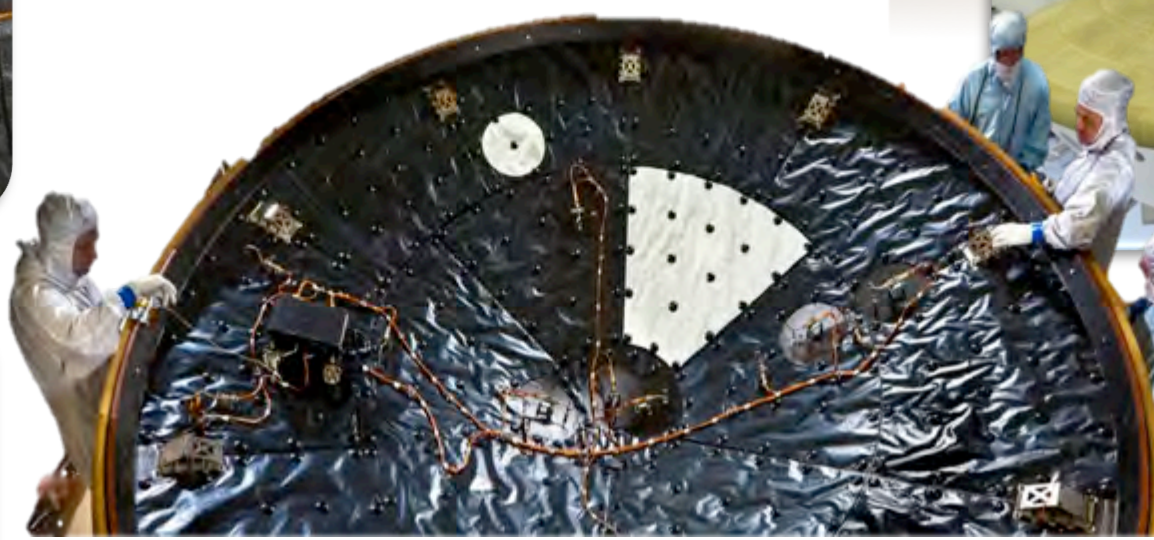
Dr. Neil Cheatwood
MEDLI PI
STMD/GCD EDL PI

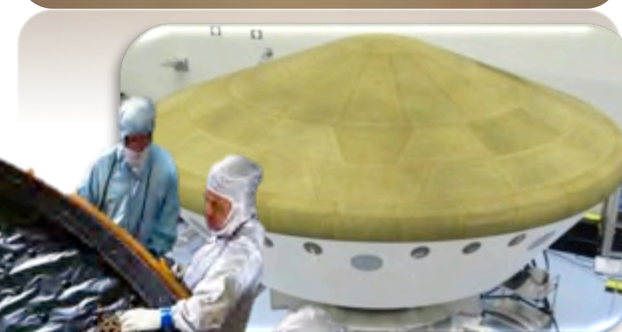
MEDLI: MSL Entry, Descent and Landing Instrumentation

- **MEDLI consists of 7 pressure ports, 7 integrated sensor plugs, and support electronics**
- **Gathered engineering data during entry and descent for future Mars missions:**
  - Aerothermal, aerodynamic, and thermal protection system performance
  - Atmospheric density and winds

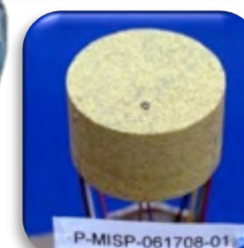
Sensor Support Electronics

Mars Entry Atmospheric Data System (MEADS)



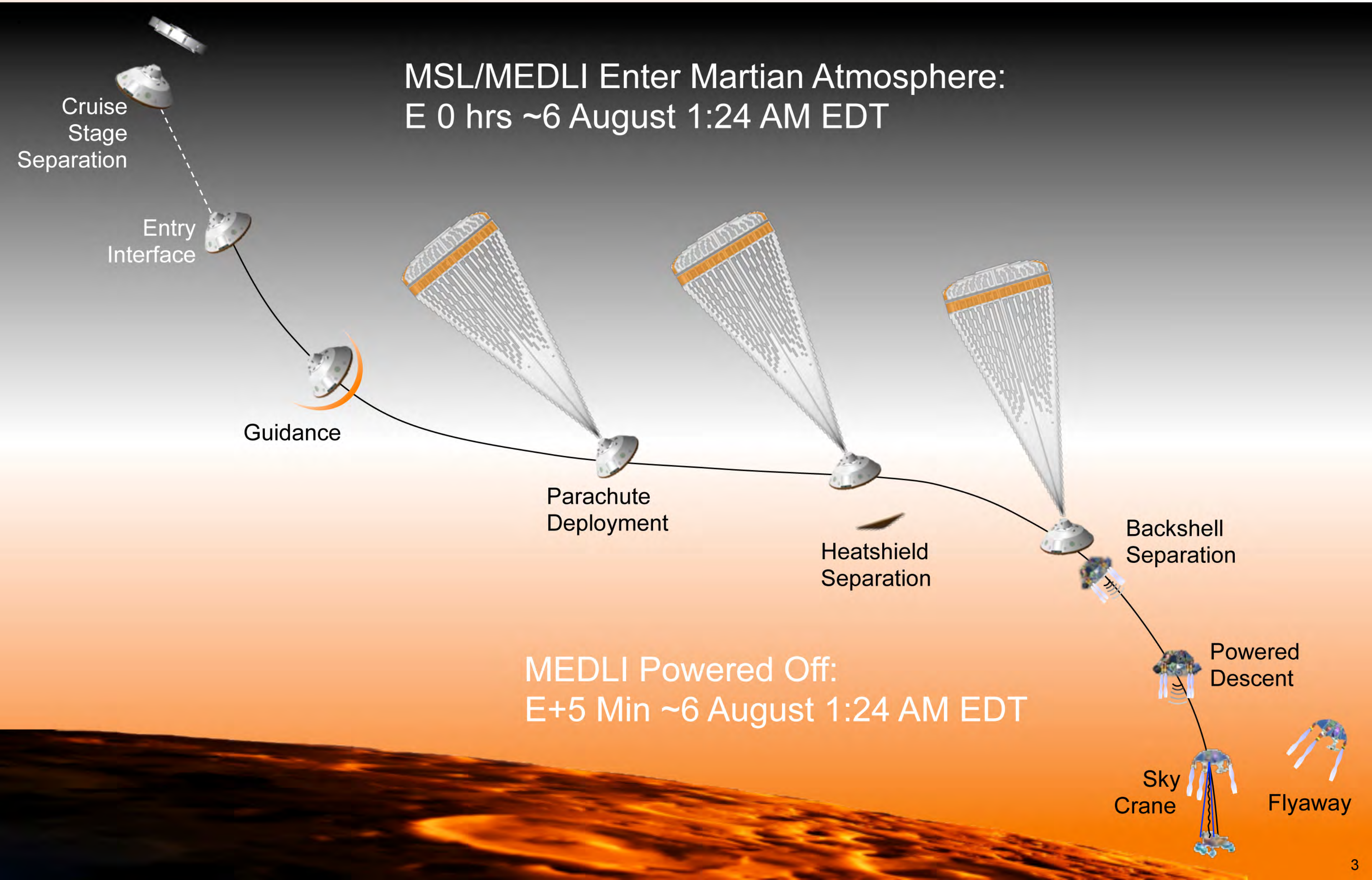


The MEDLI instrumentation makes MSL the first extensively instrumented heatshield ever sent to Mars



MEDLI Instrumented Sensor Plug (MISP)

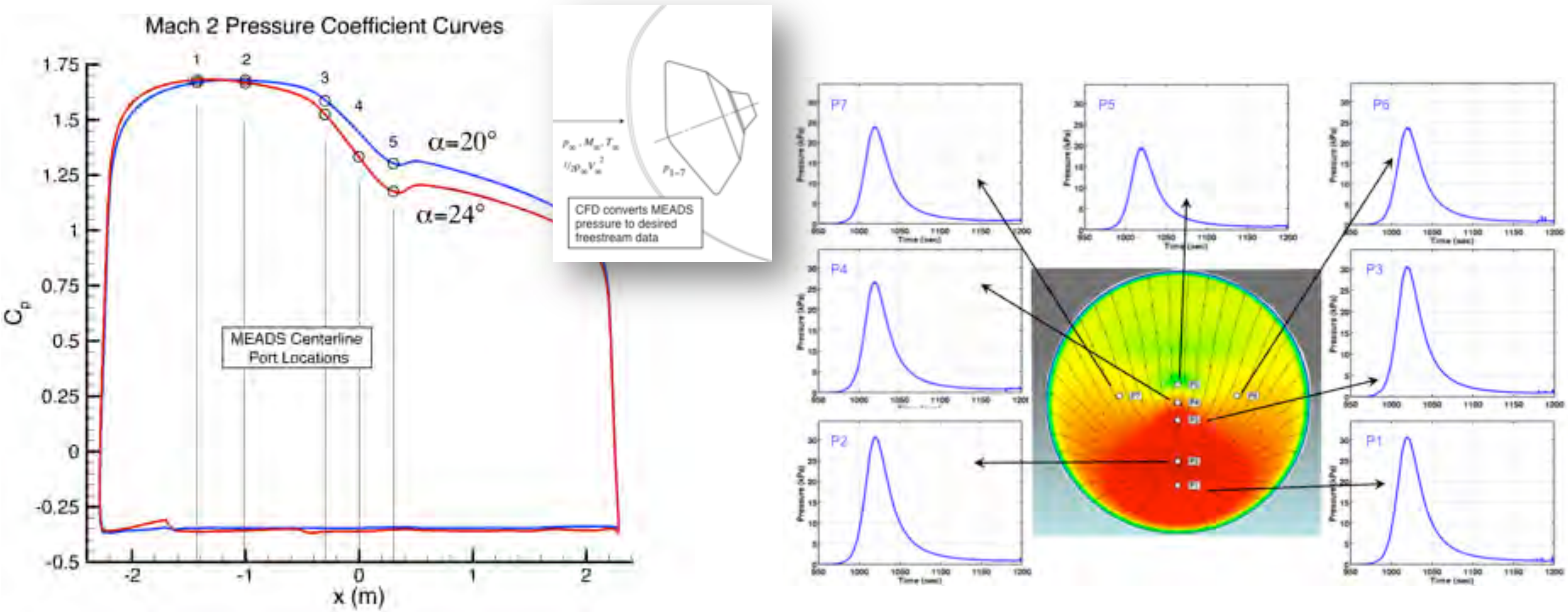
MSL Entry, Descent and Landing (EDL) Sequence



MEADS Data: What Did We Measure?

MEADS measured 7 forebody pressures behind a bow shock wave

- **MEADS algorithm matches 7 MEADS pressures to best fit LAURA CFD predicted pressures**
  - Identifies: alpha, beta at the best-fit CFD surface
  - Pressure magnitudes with CFD determines dynamic pressure
  - Mach can be extracted with or without IMU velocity data (IMU helps greatly)
- **Angle measurements are relative to the approaching velocity vector seen by the heatshield**

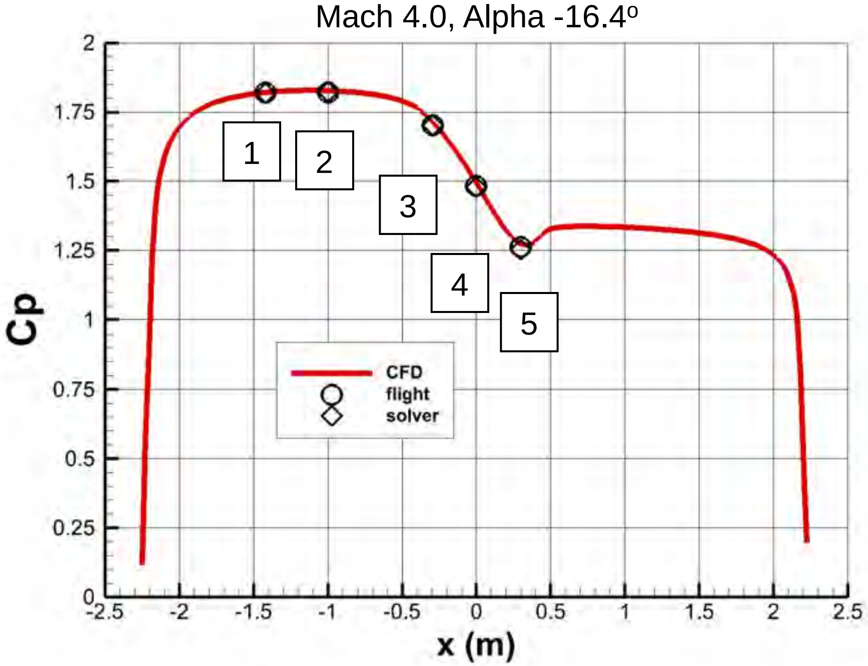


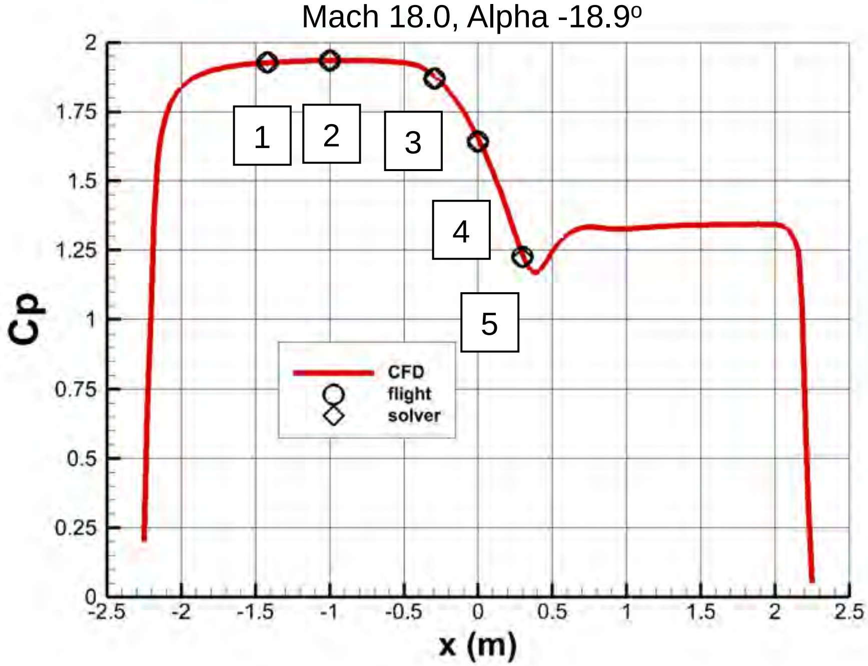
Comparison of MEADS Pressures and CFD Surface

MEADS/DIMU combined reconstruction converged to CFD surface predictions very well

- **MEADS measurements appear to be very clean and agree very closely with CFD predictions**
  - Ports 1, 2 determined stagnation pressure accurately
  - Residuals for all ports over entry MEADS-Valid range (q > 850 Pa) are ~1% of READING or less (much less over much of the trajectory)

Examples of MEADS Centerline Ports
Measured (flight) vs. interpolated CFD (solver)

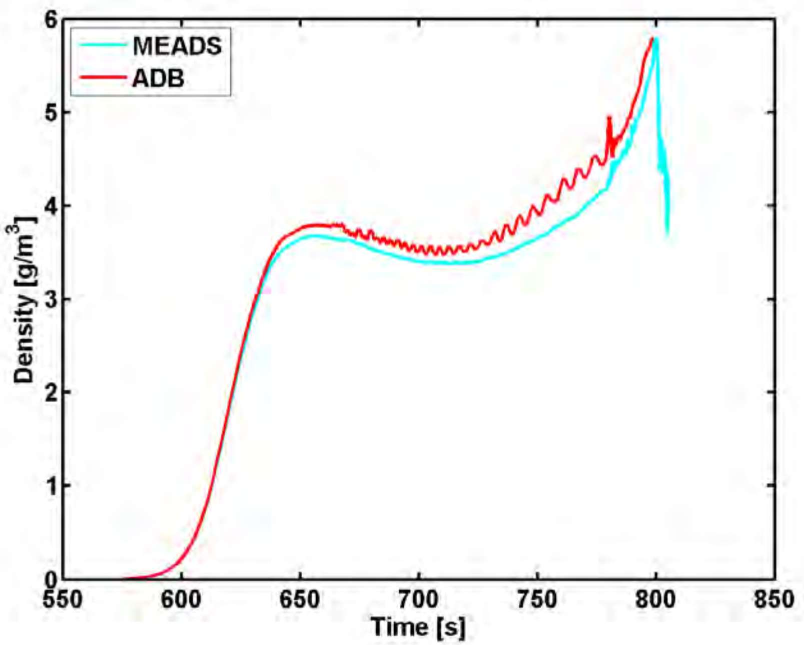




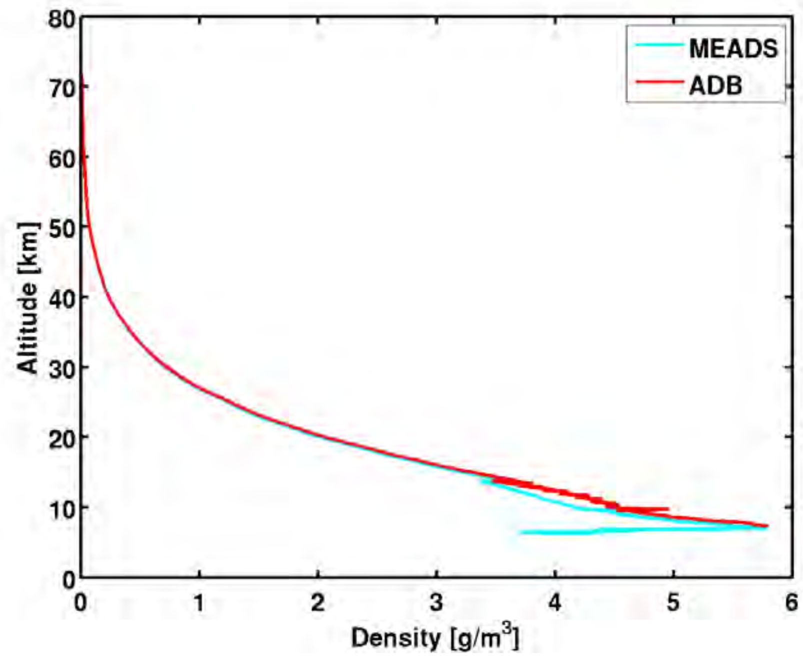
Reconstructed Density

Density can be determined from accelerometer a reconstructed freestream velocity using dynamic pressure (from MEADS) or the preflight axial force coefficient (ADB). Both versions show very close agreement until low altitudes and velocities.

- Currently the IMU reconstruction assumes no wind velocity (solid mass of atmosphere rotating with Mars)
- The slower the capsule velocity, the greater the error from winds when extracting density and freestream velocity out of dynamic pressure measurements
- Preliminary sensitivity studies show that the two density profiles can be brought into close agreement by solving for a best-fit prevailing eastward wind

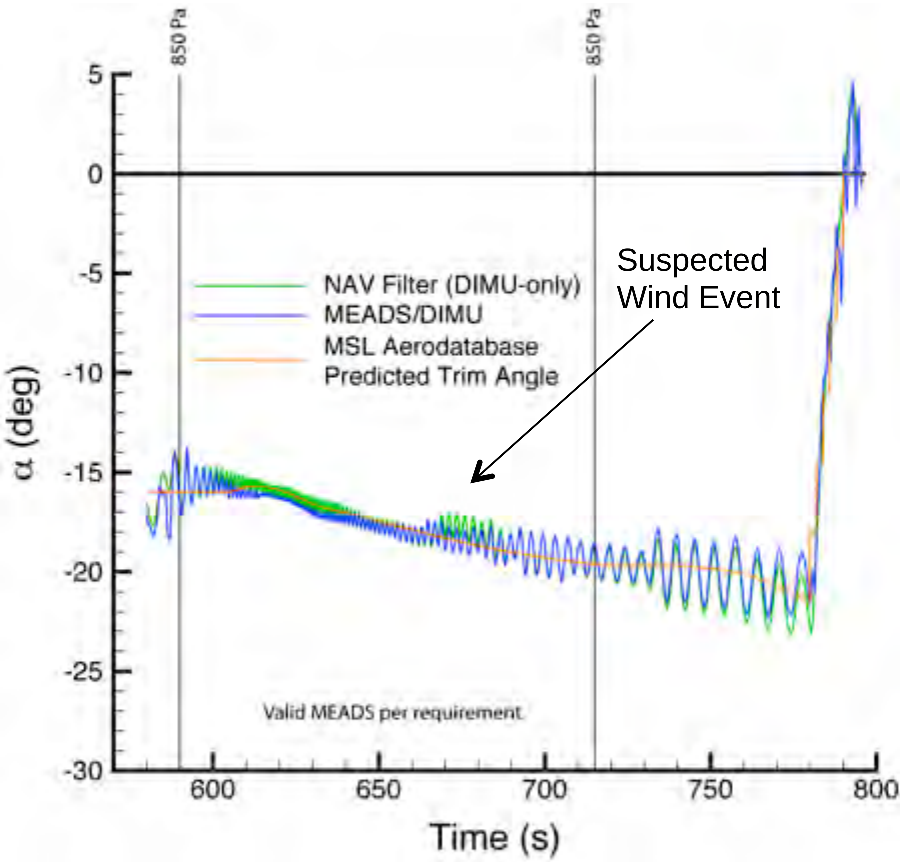


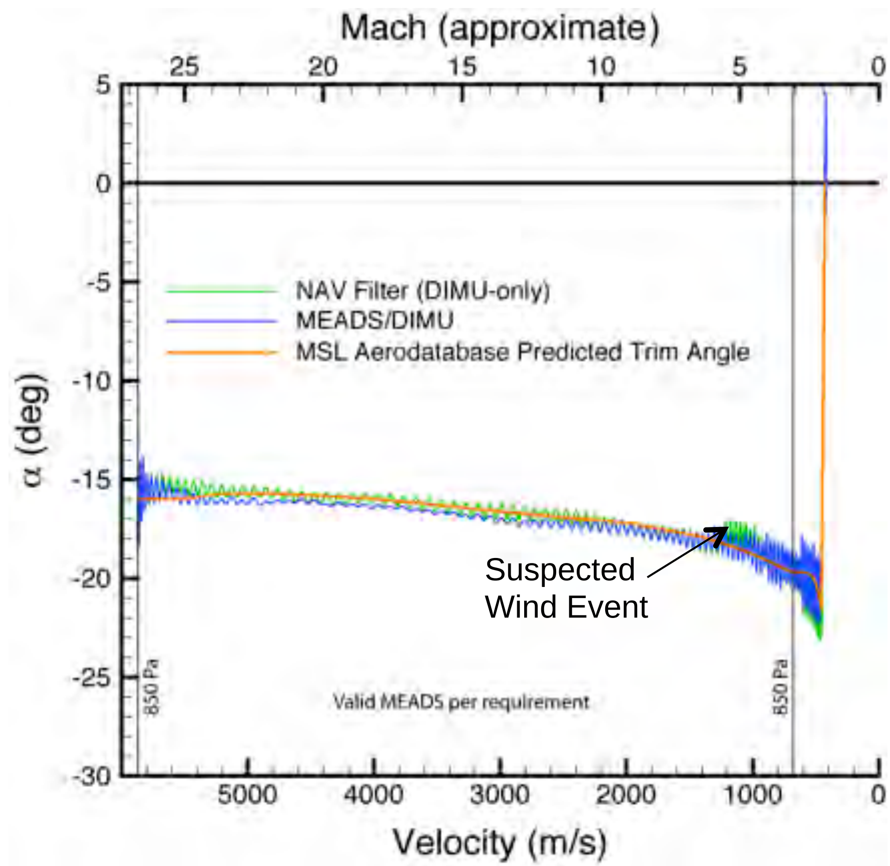
Altitude (km)



Reconstructed Angle of Attack

- **Excellent agreement between reconstructed angles of attack and preflight predictions**
- **MEADS differs from DIMU (and predicted) by ~0.4 deg in hypersonic regime (better at supersonic speeds)**
- **Disagreement at 675 sec appears to be significant wind event (fly through “jet stream”)**
  - Focused study pending

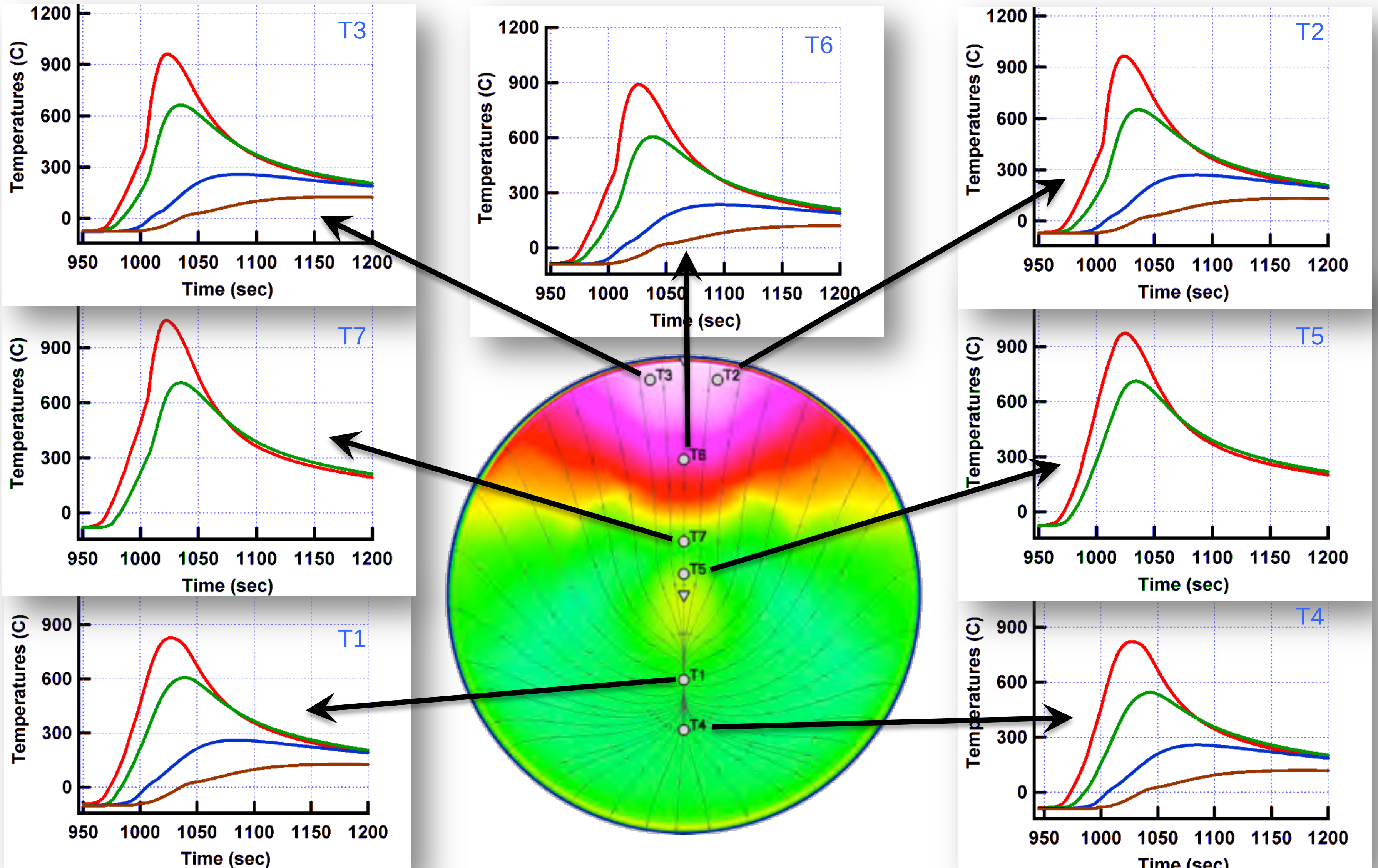




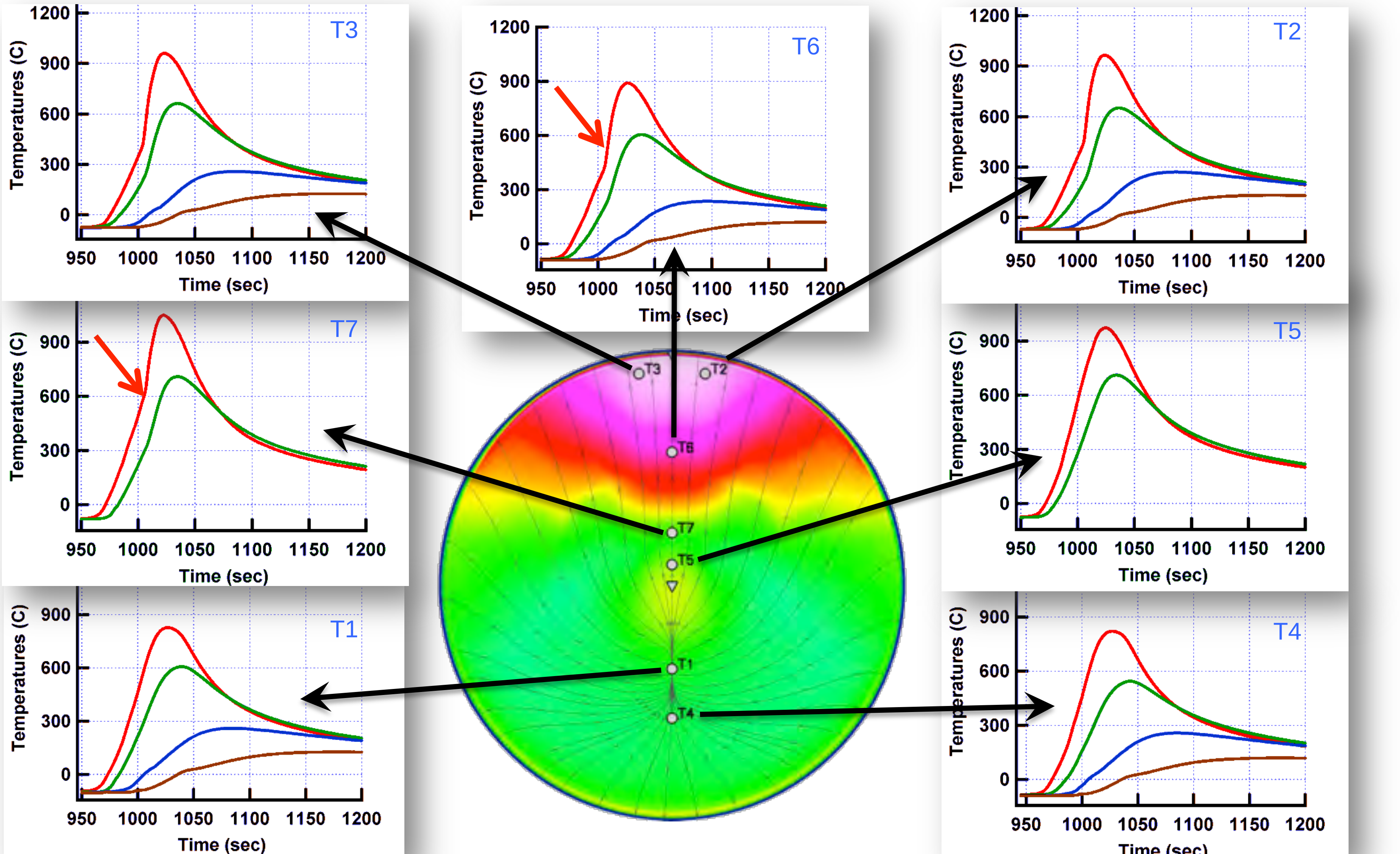
Preliminary MEADS Conclusions

- The MEADS experiment collected a very clean set of 7 port pressures
- Comparisons to date show MEADS has separated C_A from dynamic pressure to within 2% (PRELIMINARY FINDING!)
- Reconstructions show the MSL Aerodynamic database predicted entry performance very well (trim angle, L/D, Drag)
- Preliminary comparisons suggest we may be able extract prevailing wind during entry as well as the magnitude of at least one significant wind shear event
- As expected prior to flight, MEADS accuracy is dominated by CFD uncertainties
- Next: Kalman filtering of all available data will identify a best fit with uncertainties

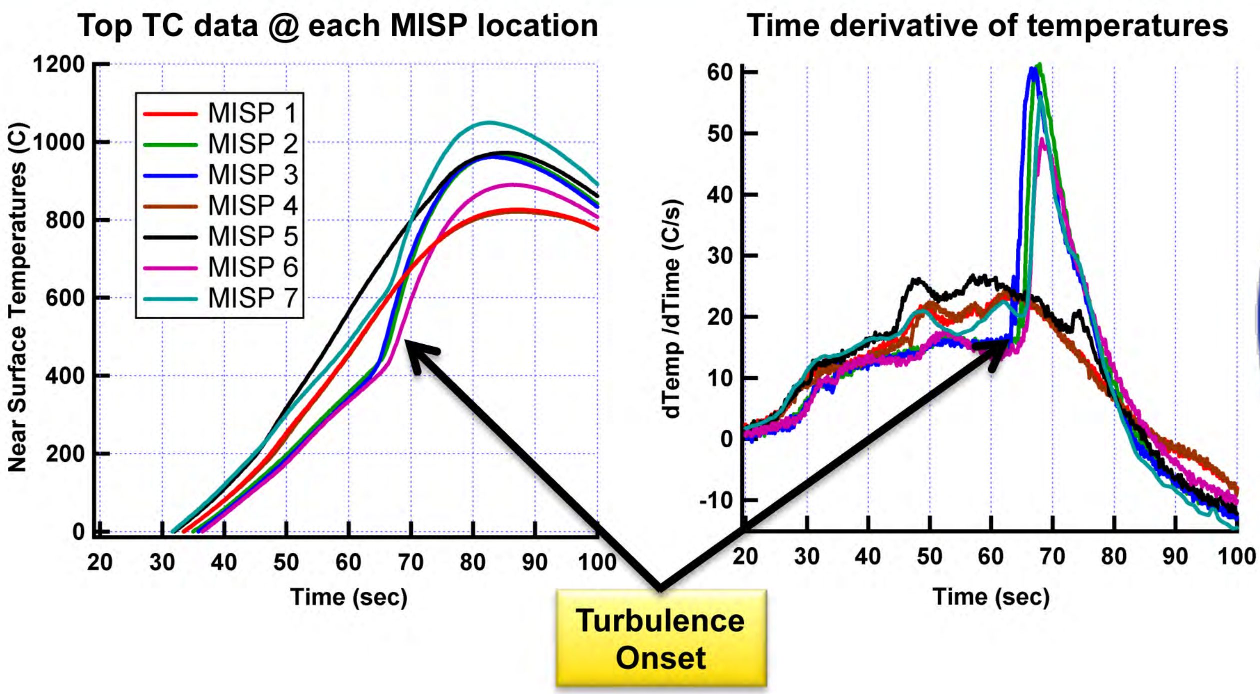
MISP Thermocouple Data

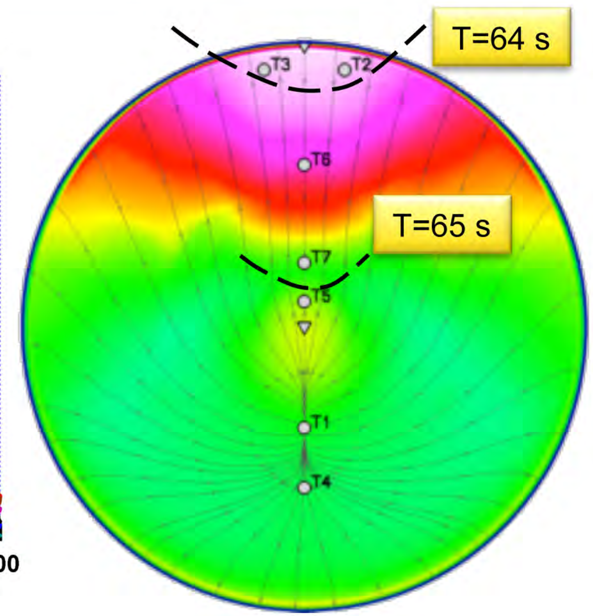


Onset of Turbulent Flow



Boundary Layer Transition to Turbulence



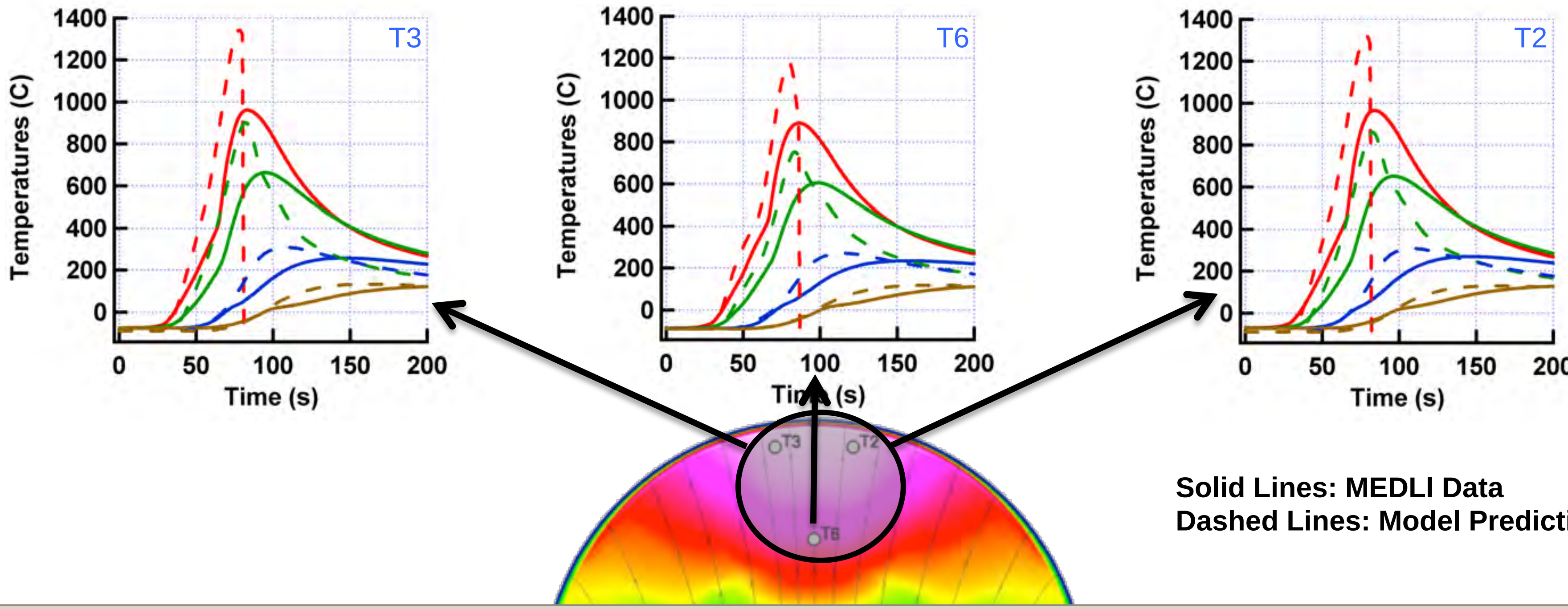


Turbulent Onset Time

Plug Location	Flight	Reθ=200
	Sec	Sec
MISP 3	63	56
MISP 2	64	56
MISP 6	65	58
MISP 7	65	70

- **Onset of turbulence evident in MEDLI temperature data**
- **Transition front moves from leeside forward until it reaches MISP 7**
- **The wind-side flow remains laminar**
- **Turbulence occurs later than predicted (using Reθ=200 correlation) and proceeds to MISP 7 within 2-3 seconds**
- **The possibility of tripped (roughness induced) turbulence being explored**

Leeside Turbulent Region Temperature Comparison



Solid Lines: MEDLI Data
Dashed Lines: Model Predictions

- Significant turbulent heating predicted in the leeside region
- Heatshield design environments were taken at these points
- While onset of turbulent flow is evident, the heating augmentation is significantly below prediction
  - – This appears to be the most significant finding from the MEDLI-MISP data

Summary: Nominal Model Predictions vs. MISP Data

- **Maximum Temperature (at 0.1-in initial depth):**
  - Leeside Turbulent Region: Predicted temperature 1325 ^{o}C vs. 965 ^{o}C in flight
  - Apex Region: Predicted temperature 839 ^{o}C vs. 1050 ^{o}C in flight
  - Stagnation Region: Predicted temperature 709 ^{o}C vs. 820 ^{o}C in flight
  - Possible Causes
    - Inadequate prediction of boundary layer transition to turbulence
    - Low turbulent augmentation
    - Low recession
    - Inadequate shock layer chemistry model

Model Predictions not Conservative

- **Onset of Turbulent Flow:**
  - Transition to turbulence occurred later in flight than predicted
    - Predicted 56 sec, observed in flight at 63 sec
  - Transition front moved upstream quickly, slower movement was predicted
  - Roughness induced transition being explored as possible cause
- **TPS Recession:**
  - Recession estimated less than 0.1 in, smaller than nominal predicted recession of 0.16 in.
  - Finite rate surface chemistry is believed to be the cause

Summary

- **All MEDLI sensors worked extremely well and returned data**
- **MEDLI data has identified differences between model predictions and measurements**
  - Allows for improvement of models
- **High level NASA commitment essential to obtain engineering measurements for future mission benefit**
- **Value of calibration/characterization to quantify errors/uncertainties**
  - Enables proper understanding of flight measurements
- **Instrumentation of New Frontiers/Discovery class missions necessary to expand tool validation with flight datasets**
  - Technology investments required to reduce instrumentation footprint
- **Additional instrumentation improves landing ellipse precision**
  - Backshell temperature and pressure
  - Parachute camera
  - Radiant heating
  - Etc.

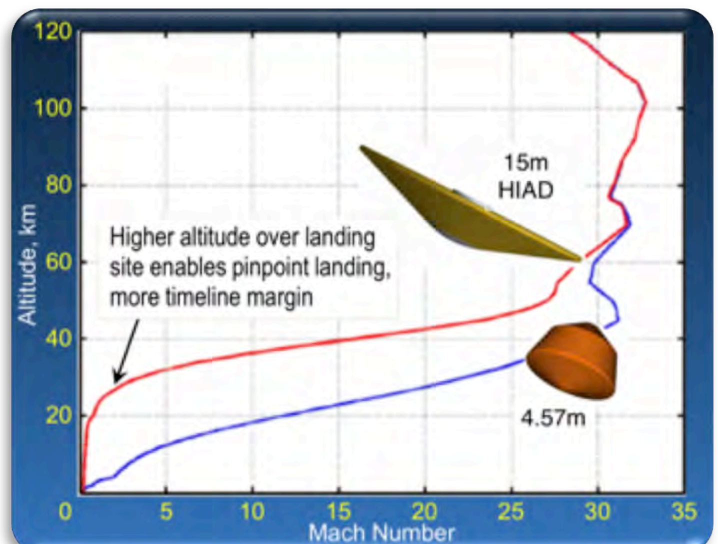
Hypersonic Inflatable Aerodynamic Decelerator (HIAD)

- **Mars thin atmosphere makes it difficult to decelerate large masses and limits accessible surface altitudes. Science payload size and site altitude are limited by Viking EDL architecture.**
- **Aeroshell size limited by Launch Vehicle fairing**
- **Improved payload access**
- **Lower ballistic coefficient from increased drag area allows higher altitude deceleration (aerocapture or entry) providing access to higher surface elevations, increase in landed mass, and longer EDL timelines.**

IRVE-3 was a flight test of HIAD technology

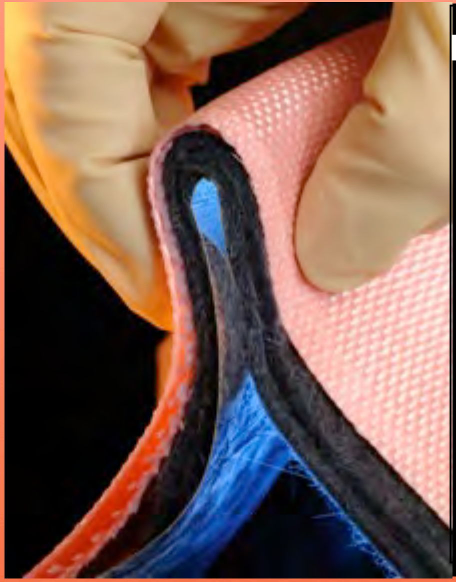
MSL	HEART
m=3300 kg	3500 kg
D=4.5 m	8.5 m
BC=125 kg/m^2	40 kg/m^2

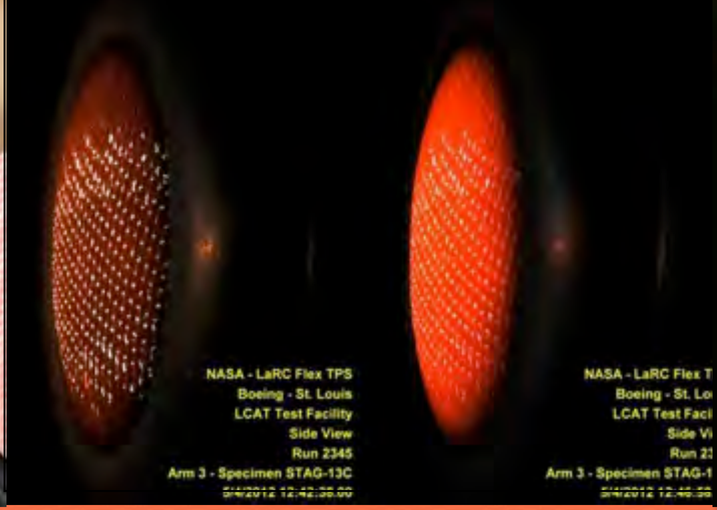
Comparable Entry Masses



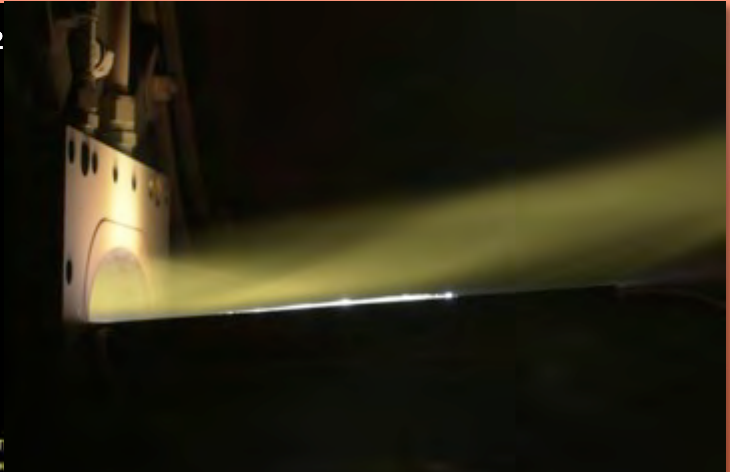
Flexible Thermal Protection Systems

- *Developed new arc jet testing methods for both shear and stagnation tailored to FTPS.*
- *Completed over 100 test samples in the Boeing LCAT Arc Jet Facility to verify Gen 1 FTPS for IRVE-3 (20 w/cm2 heating) and HEART (30-40 w/cm2). Initial tests of lower TRL materials in support of Gen 2 were also tested.*
- *Delivered three 3-m FTPS units (IRVE-3 EDU, IRVE-3 flight unit and the 3-m NFAC unit).*
- *Thermal model version 0.1 was released for Gen 1 FTPS*





Boeing LCAT Stagnation Test (50 W/cm^2

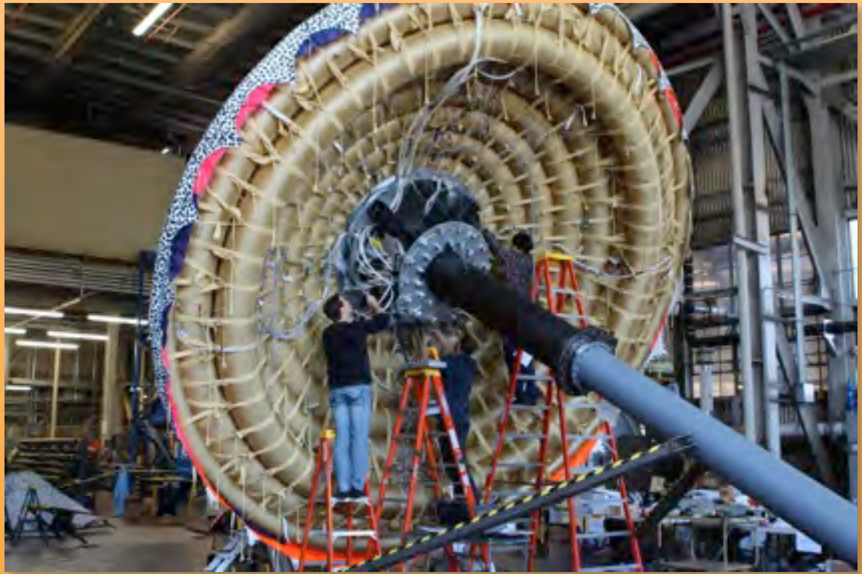


Boeing LCAT Shear Test

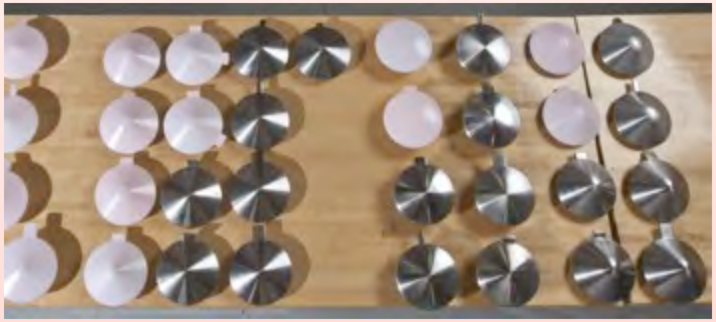
Inflatable Structures

- *Fabricated a 6-m inflatable structure (manufacturability at a large scale)*
- *Aero loads testing at NFAC (3-m w/ TPS, and 6-m)*
- *First time use of full-field photogrammetry (4 systems) in a wind tunnel*
- *ARC designed pressure ports on the flexible materials*
- *IDIQ contract awarded 47M (ILC Dover, Lockheed Martin, Airborne)*
- *Completed 10-m conceptual design task*
- *3 tasks awarded for Elevated Temp Article, Elemental Test article and 6-m Article*

Installation in 40 x 80 ft Test Section



HIAD Next Generation Subsystems

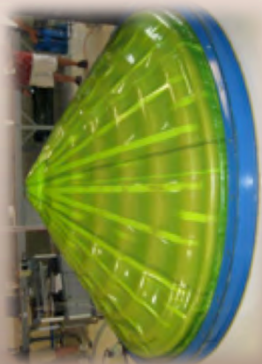


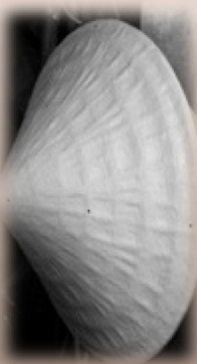
Quantified the supersonic aerodynamic performance of parametric trim tabs as an alternative to ballast mass

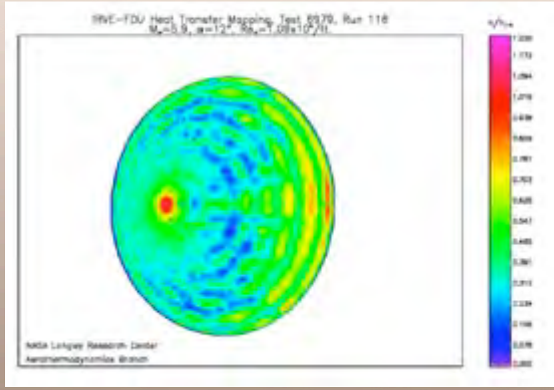
In less than 6 months, 38 models were designed, built by LaRC fabrication, and completed 120 hours of testing in the Unitary Wind Tunnel.

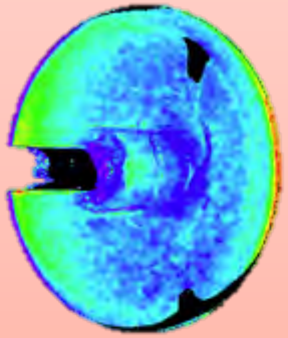
Measured the aerodynamic heating on HIAD-relevant fore-body surface deformations in LAL Hypersonic wind tunnels (240 hours).

Ceramic models with thermo-phosphor coating that give global heating measurements of entire model









As payloads become wider/longer and/or higher L/D is needed, the centerbody could experience higher heating. Measured the aerodynamic heating on HIAD-relevant centerbody geometries.

LaRC 20-Inch Mach 6 & 31-Inch Mach 10 tunnels used to measure heating on various centerbody geometries (160 hours).

Mission Applications

Developed and enhanced key EDL system models; enabling the evaluation of HIADs within the concept of operations of direct entry and aerocapture missions at Earth and Mars.

Convective and raditative heating, trade space models

Landing system mass models (crushable materials and air bag systems)

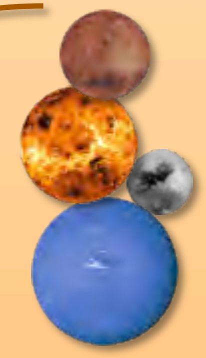
Supersonic retro propulsion mass model

Completed trade studies demonstrating the applicability of HIADs, and the recommended HIAD scale, within high priority robotic and human exploration missions at Earth and Mars

- *Direct entry to Mars Southern Highlands (0-4 km MOLA)*
- *Mars aerocapture in support of human exploration*
- *MPCV L2 and lunar return*
- *MPCV fast transit (Mars return)*
- *Launch vehicle asset recovery (Space-X Falcon 9)*

Identified the sensitivity of recommended HIAD scale to mission parameters (entry conditions) and key assumptions such as flexible TPS performance limits

6 –25 meter HIAD Class



Robotic Missions (entry or aerocapture):
- *Mars*
- *Venus*
- *Titan*
- *Neptune (and other gas giants)*

Robotic or Crewed Earth Return (entry or aerocapture):
- *LEO (including ISS)*
- *GEO, NEO, Lunar*

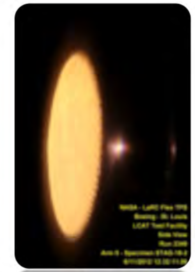
DoD Applications

Technology Development & Risk Reduction for Human Mars Missions

HIAD FTPS: Path Forward

Ground Testing & Implementation

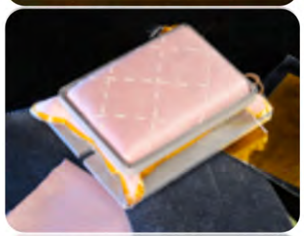
Catalycity Testing
UVM – 2011



Stagnation Testing
LCAT– 2012

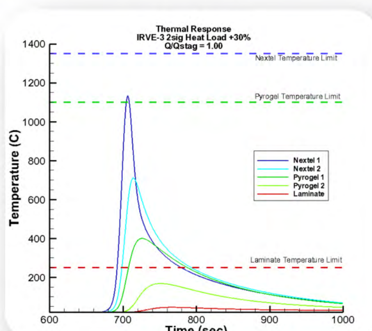
TPS EDU for 6 m IAD – 2012-2013

IRVE-3 Nose Cap Test
TP2 – 2011



Shear Testing
LCAT – 2011-2012

Modeling & Analysis



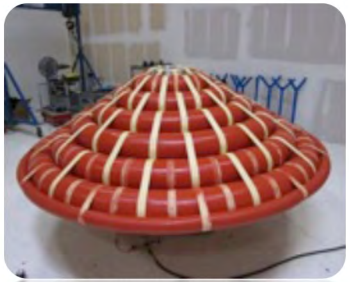
1-D Model (Test correlated) 2009-2012

1-D Model Physics Based Model 2011-2012 (Coming Soon)

TPS Margin Policy (Monte-Carlo Based – 2012)

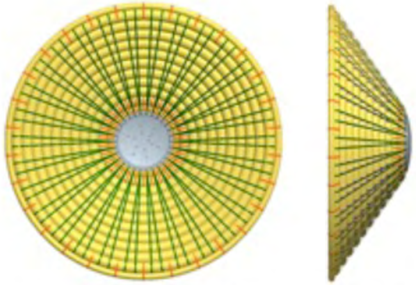
Inflatable Structure: Path Forward

Ground Testing & Implementation



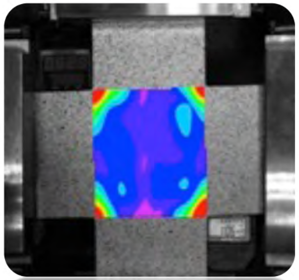
Static Load Test
3m (2011-2012)

Aero Load/Deflection Test
6 m Dia (NFAC-2012)

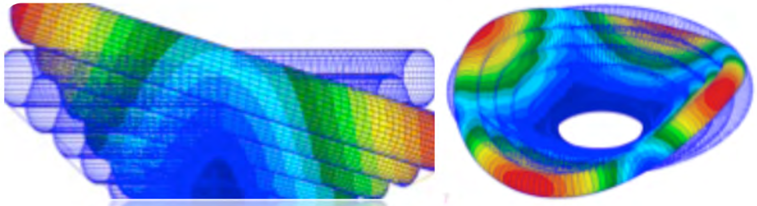


Load/Deflection Test (w/ TPS)
6 m Dia (2013/2014)

Modeling & Component Testing

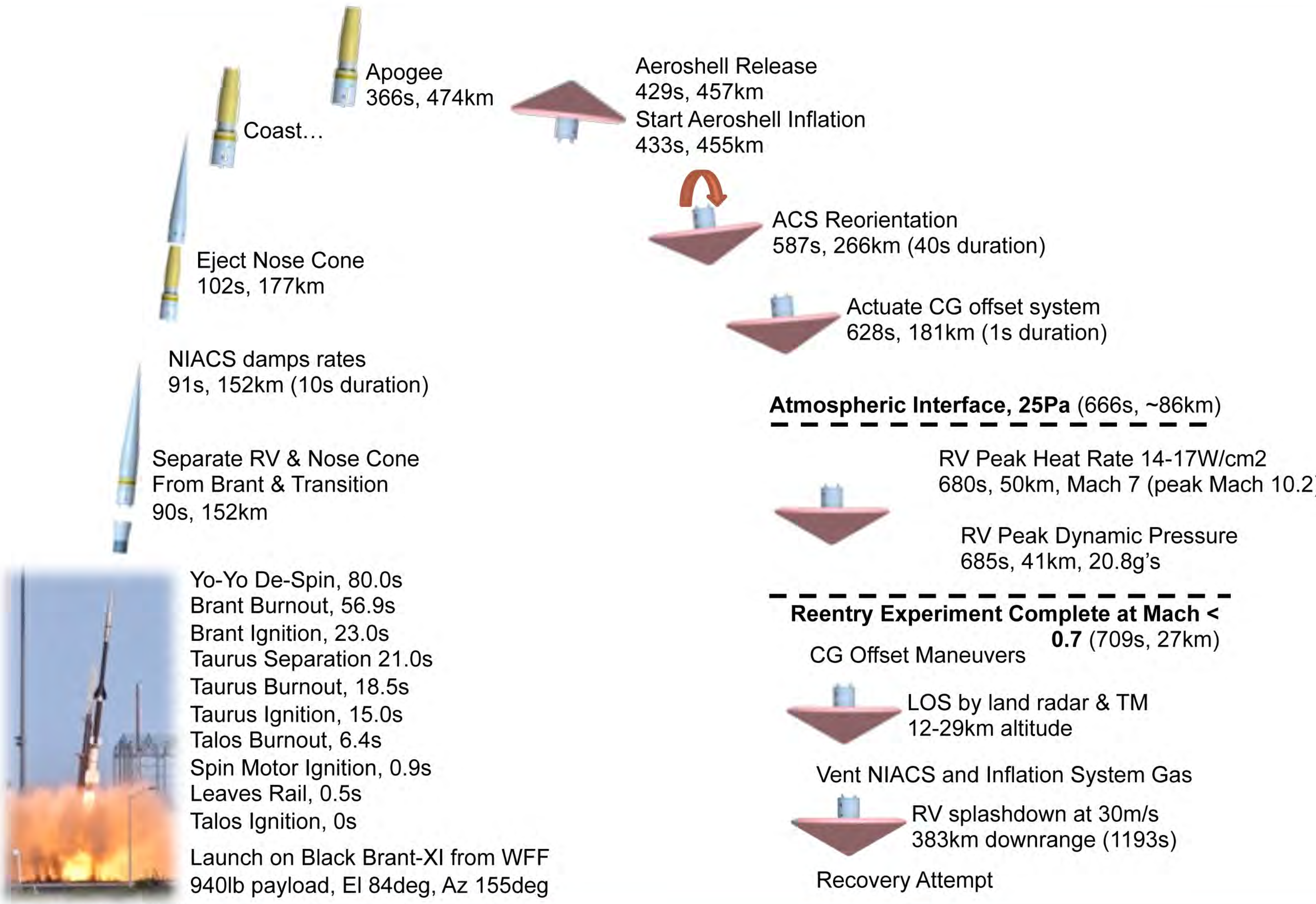


Inflatable Structure material property characterization



Structural Modeling capability

IRVE-3 Nominal Mission



Success Criteria Assessment

Minimum Success Criteria

Title	Description	Status	Flight Results
RV Separation	The RV separates from the LV and nose cone assembly and does not re-contact either component.	G	No re-contact shown in video; checking IMU data.
RV Aeroshell Inflation	The RV inflatable aeroshell inflates to the designed shape prior to atmospheric interface.	G	Geometry looks good on video; processing drag data.
RV CG Offset Configuration	The RV reconfigures to generate a known radial CG offset prior to atmospheric interface.	G	CGO string pots measured translation distance.
RV Flight Performance	The RV flight performance data is captured from atmospheric interface through the end of the flight experiment.	G	Flight data was captured from launch past the end of the experiment.

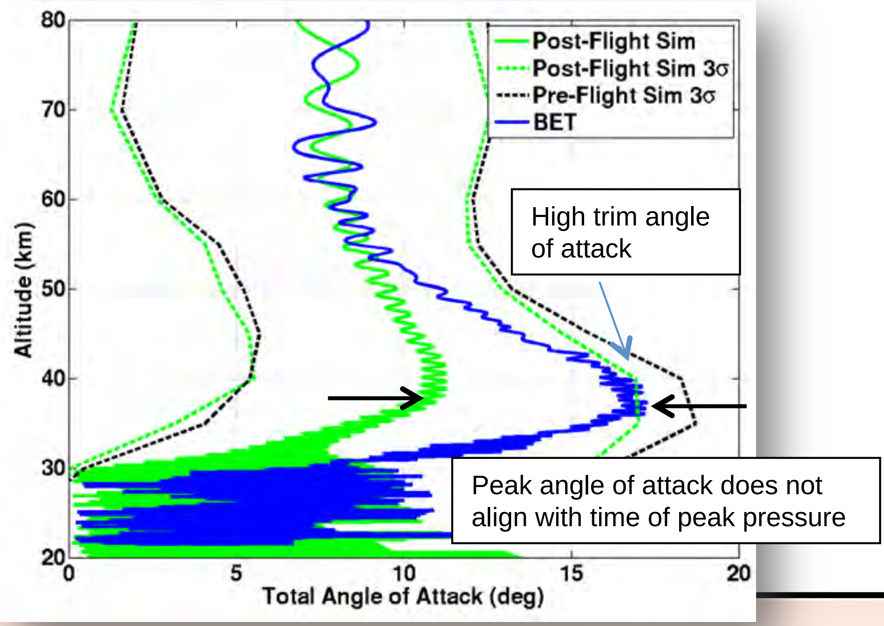
Success Criteria Assessment

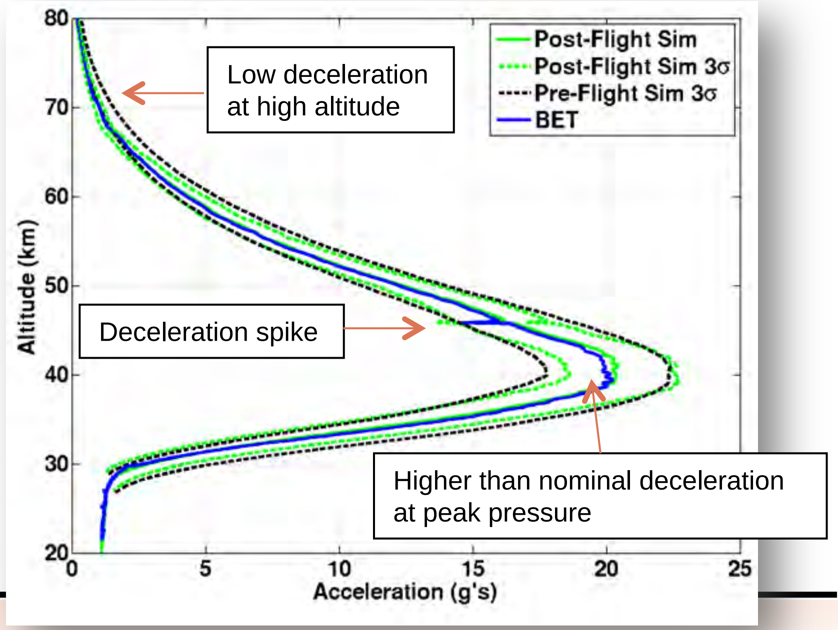
Comprehensive Success Criteria

Title	Description	Status	Flight Results
RV Data Set	The RV data set as specified in the Mission Telemetry Requirements (MTR) document is captured from launch through the end of the flight experiment.	G	Data was captured from launch past the end of the experiment.
RV Body Axis Alignment	At atmospheric interface, the Attitude Control System (ACS) has aligned the RV body axis with the trim angle of attack within 5 degrees, with a total rate of change less than 10 degrees/sec.	G	Attitude looks good in video data; processing IMU data.
RV Roll Angle	The ACS maintains a RV roll angle of 0 degrees ± 5 degrees from atmospheric interface through the end of the flight experiment.	G	No spin-up in video data; processing IMU data.
RV Aeroshell Inflation Maintenance	The RV maintains inflation from atmospheric interface through the end of the flight experiment.	G	RV maintained inflation past the end of the experiment.
RV Reentry Heating	Flight data confirms that the aeroshell experienced reentry heating of at least 12 W/cm2 (cold wall).	G	Flux sensor indicated 15.6W/cm2; verifying with CFD.

IRVE-3 Best Estimated Trajectory (BET)

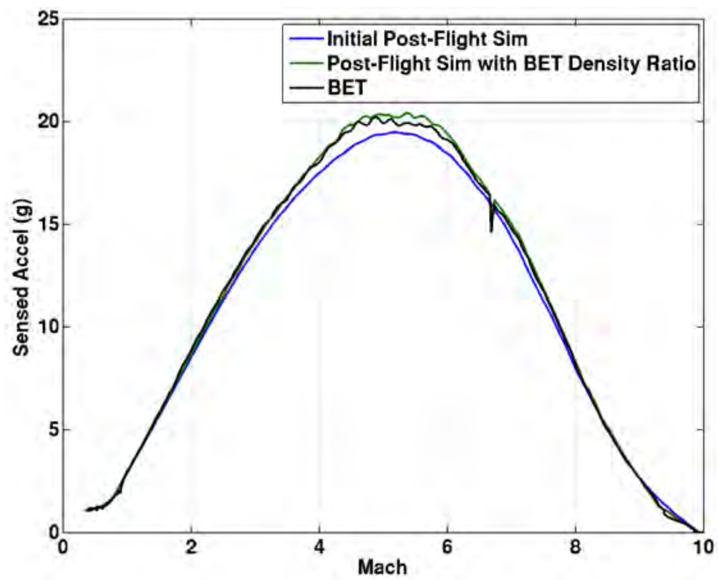
- **IRVE-3 trajectory reconstruction drives a number of post-flight analysis activities including thermal, structures, aero-performance, and flight dynamics analysis**
- **On-board instrumentation for re-entry trajectory reconstruction included:**
  - GLN-MAC (gimbaled LN-200: accelerations and body rates)
  - GPS (position and velocity observations)
  - Nose cap pressure sensors and heat flux gauges
  - 4 video cameras (shape observations)
- **Trajectory reconstruction performed in 3 steps:**
  - Pure inertial reconstruction compares well with the on-board navigation
  - GPS aiding improves attitude estimates, better captures sideslip
  - Additional aiding by the pressure measurements helps resolve density
- **The post-flight simulation captures observed launch performance which should reduce much of the dispersion seen in pre-flight trajectory estimates**

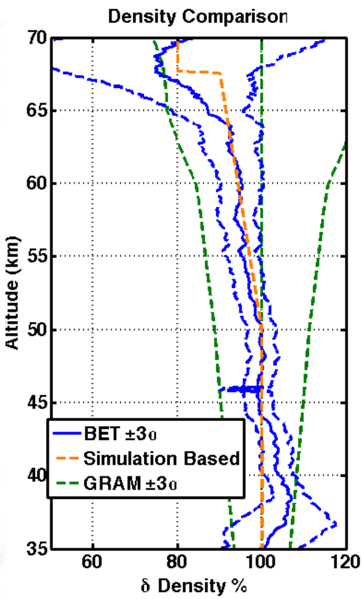




Flight Dynamics: Deceleration Profile

- **Low deceleration at high altitude**
  - Deceleration at entry-interface through 67 km less than 2-sigma low
- **High peak deceleration**
  - Deceleration at peak pressure 1-sigma high relative to the nominal post-flight estimate

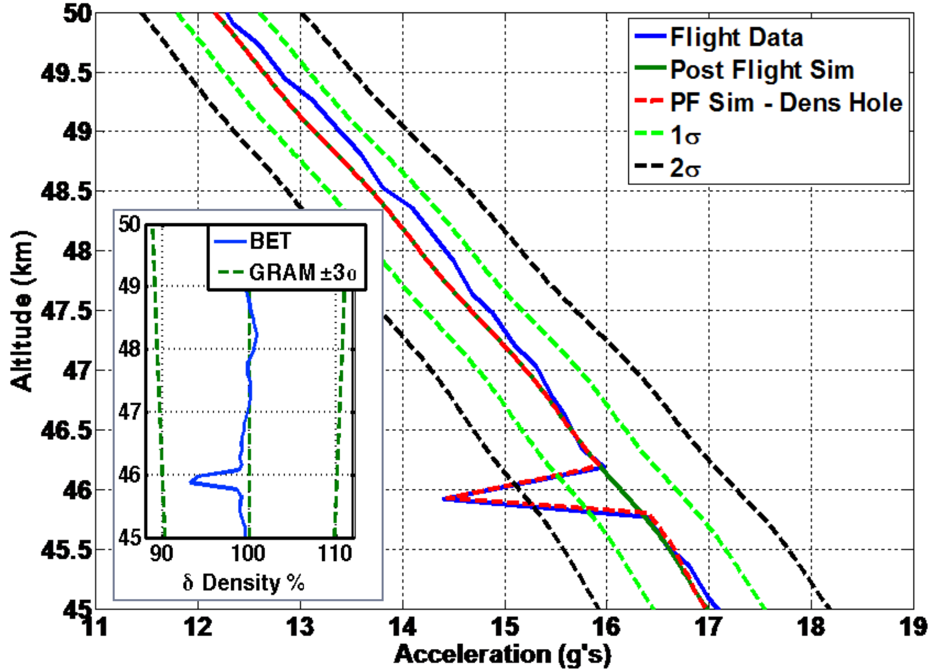




Post-Flight Analysis

Potential Cause	Analysis Findings	Disposition
Aerodynamics	• BET-based aero coefficients confirm pre-flight predicted drag performance • HIAD pressure sensors confirm that it is fully inflated at entry	Not a contributor
Atmospheric uncertainty	• Density estimates based on pressure measurements help reconcile deceleration profile during pressure pulse • Assuming nominal drag performance, simulation analysis estimates a 20% reduction in nominal density at altitude • This level of density is consistent with pressure-based estimates	Primary cause

Flight Dynamics: Deceleration Spike



Deceleration Spike

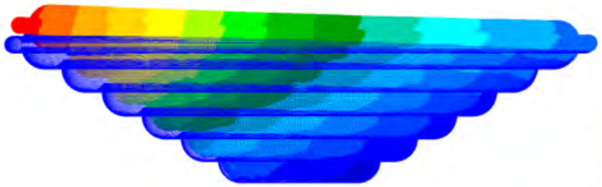
- 1.5 g reduction in acceleration over 100 msec
- Event seen in accelerometer and pressure sensor data
- Nominal deceleration profile observed before and immediately following the event

Post-Flight Analysis

Potential Cause	Analysis Findings	Disposition
Atmosphere	• Simulation studies indicate an 11% dip in density is required to reproduce the deceleration spike • Similar level of density reduction predicted in the BET based on pressure measurements	Primary cause
Structural	• Aeroshell vibration is visible in the flight video but no apparent slip or sudden deformation	Not a contributor

Structural Performance

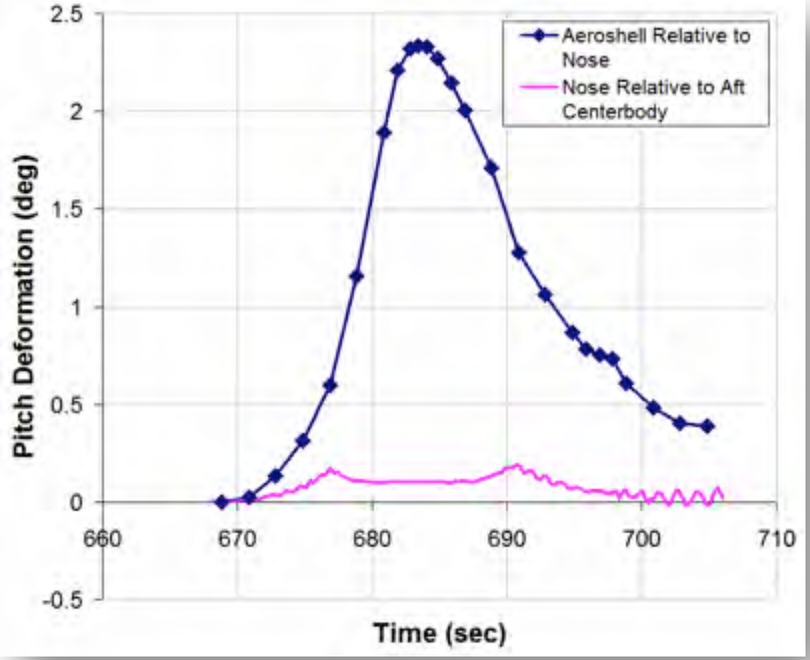
Overlaid video images at entry interface and peak pressure



FEA and CFD analysis used to predict and interpret aeroshell deflection

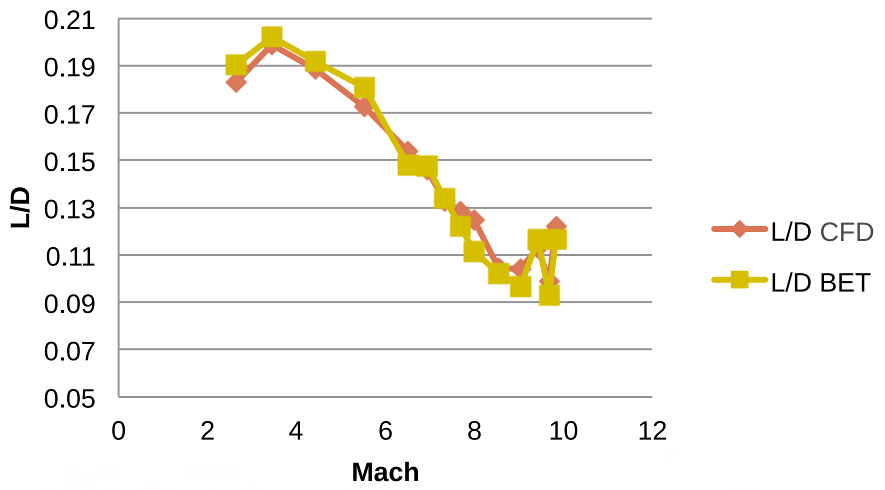
- **Structural deflections contribute to vehicle trim angle of attack**
  - Analytical models used to predict and interpret structural effects
- **Flight video used to extract aeroshell pitch deformation**
  - Landmark tracking used in the video along with overlaid frames to measure relative translation of aeroshell
  - Converted to angle by distance to rocking mode shape "pivot point" from FEA analysis
  - CG offset mechanism deflection obtained from in-flight measurements
  - Relative pitch angle of the mechanism observed to plateau at ~0.2° due to bottoming out of the bearing springs
  - Limit of 0.2° applied to post-flight simulations

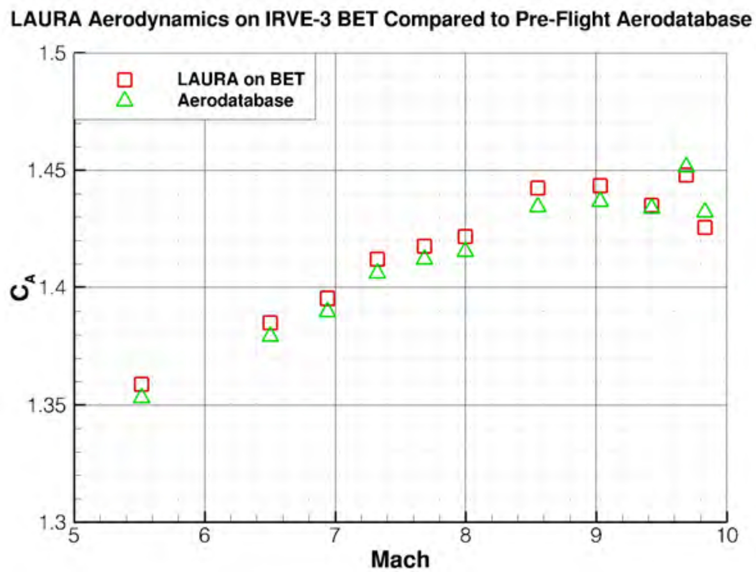
Observed Deflections

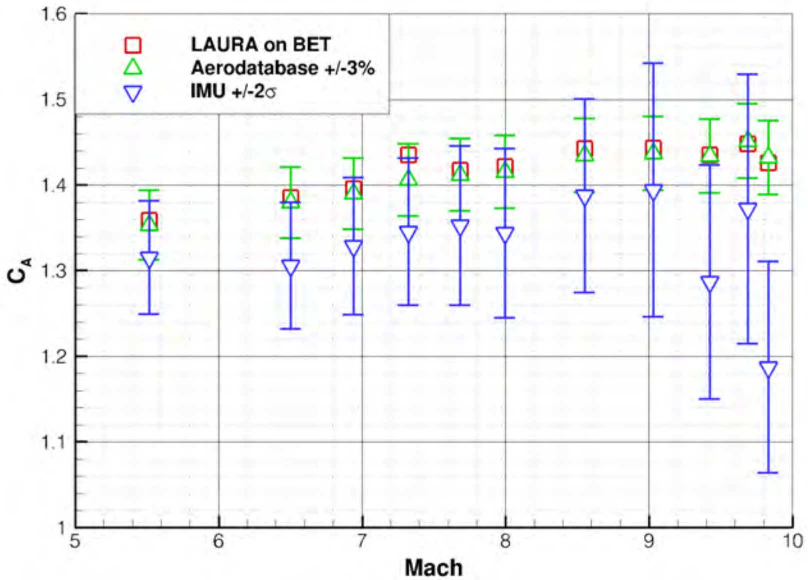


Aero Performance: Comparison to the BET

- **Aero coefficients computed from the BET**
  - Ignores ACS thrust (roll control)
  - Mass from pre-flight simulation model
- **Post-flight CFD consistent with pre-flight modeling assumptions**
- **L/D comparisons verify that the aero database force coefficients are accurate**

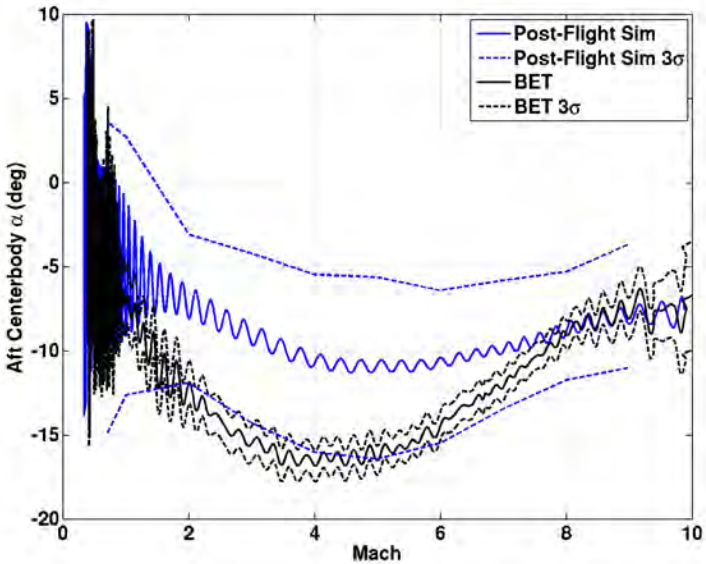






Flight Dynamics: High Angle of Attack

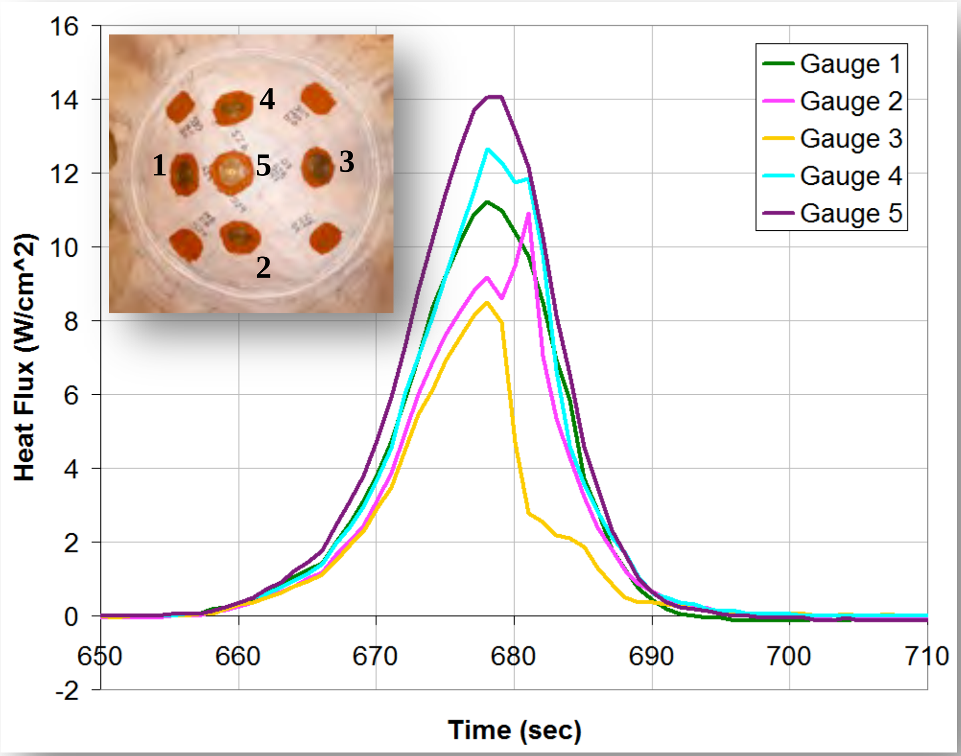
- High Angle of Attack
  - 3-sigma excursion in angle of attack during the pressure pulse
    - Growth of angle of attack with dynamic pressure indicative of aeroshell pitch deflection
  - Observed angle of attack reaches its maximum value later than simulation predicts
    - Possible aerodynamic or structural effect

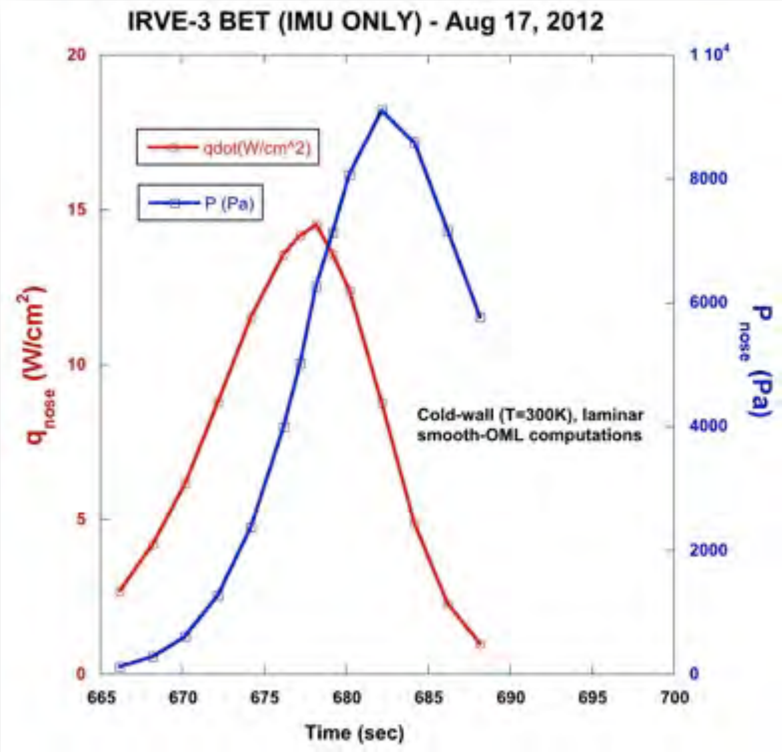


Post-Flight Analysis

Potential Cause	Analysis Findings	Disposition
Atmosphere	• Higher than predicted peak pressure due to atmosphere effects	Small Contributor
Aeroshell deflection	• Trim angle of attack is very sensitive to rotation of aeroshell due to alignment, CGO rotation, and "rocking mode" deflection	Contributor
Baseline aerodynamics	• Design OML aerodynamic uncertainties	Contributor
Other shape changes	• Change in pitch stability due to pressure distribution over deformed shape a possible contributor	Inconclusive

Peak Heat Rate

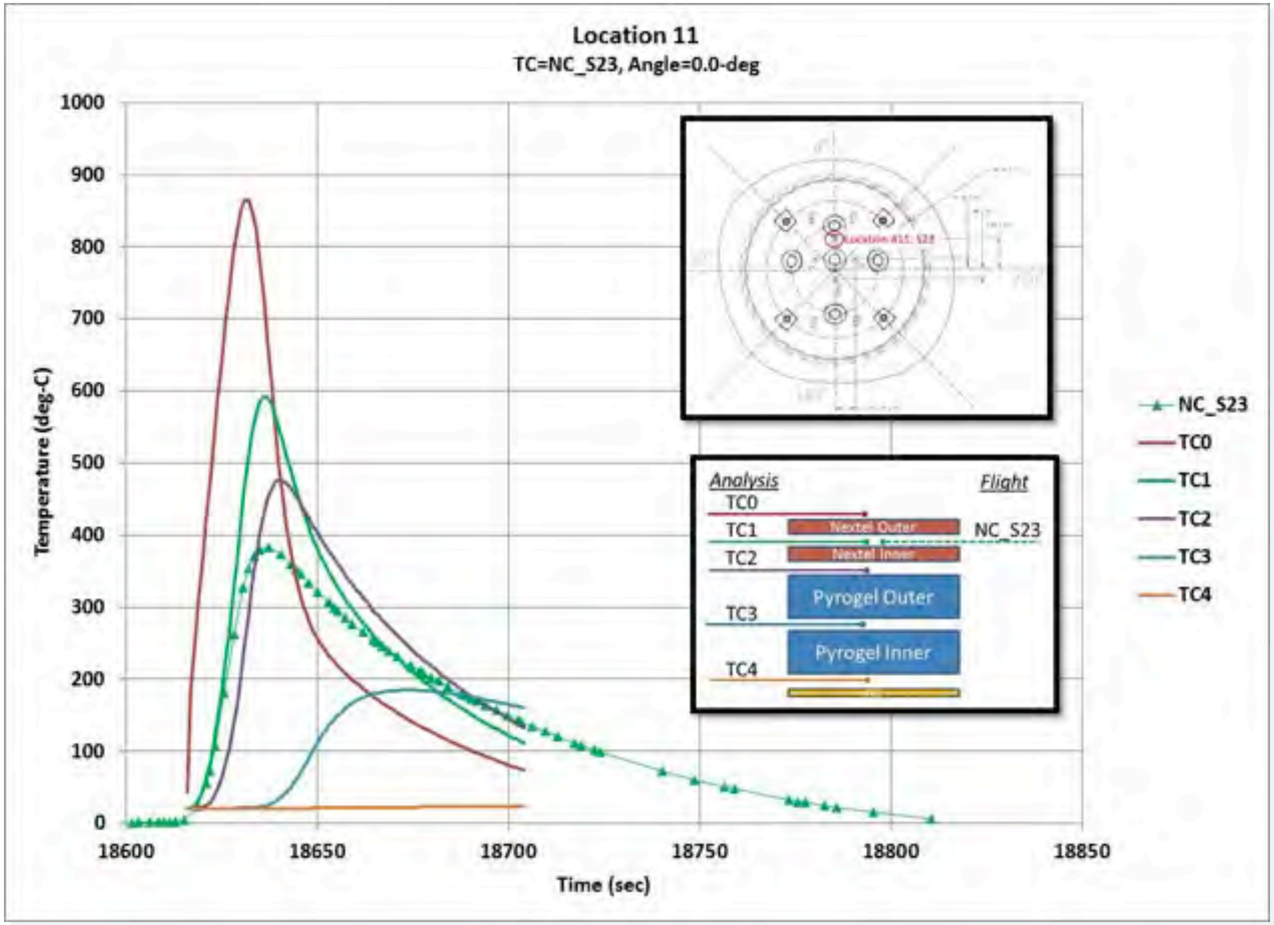




- **Measurement and calculation confirm that IRVE-3 exceeded the 12 W/cm^2 peak heat rate requirement**
  - Heat flux gauges read up to 14 W/cm^2
    - Expected uncertainty of +/- 15%
  - CFD solutions on the preliminary BET estimate a peak heat rate of 14.5 W/cm^2
    - Expected uncertainty of +/- 10%

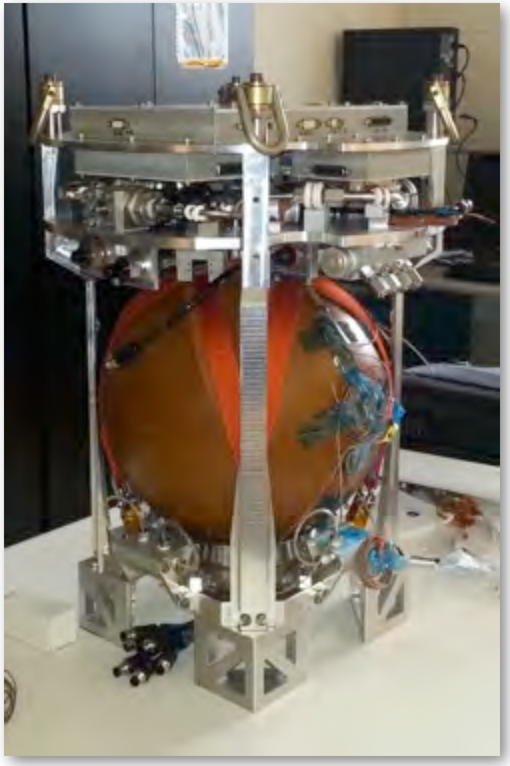
Thermal Protection System Performance

- **Analysis data does not match flight data**
  - Analysis data over predicts flight data
- **Flight data has been checked and appears to be accurate**
- **Forward Work**
  - Evaluating input data to code
    - Recovery Temperature
    - Material properties



IRVE-4 (Build to Print) Status

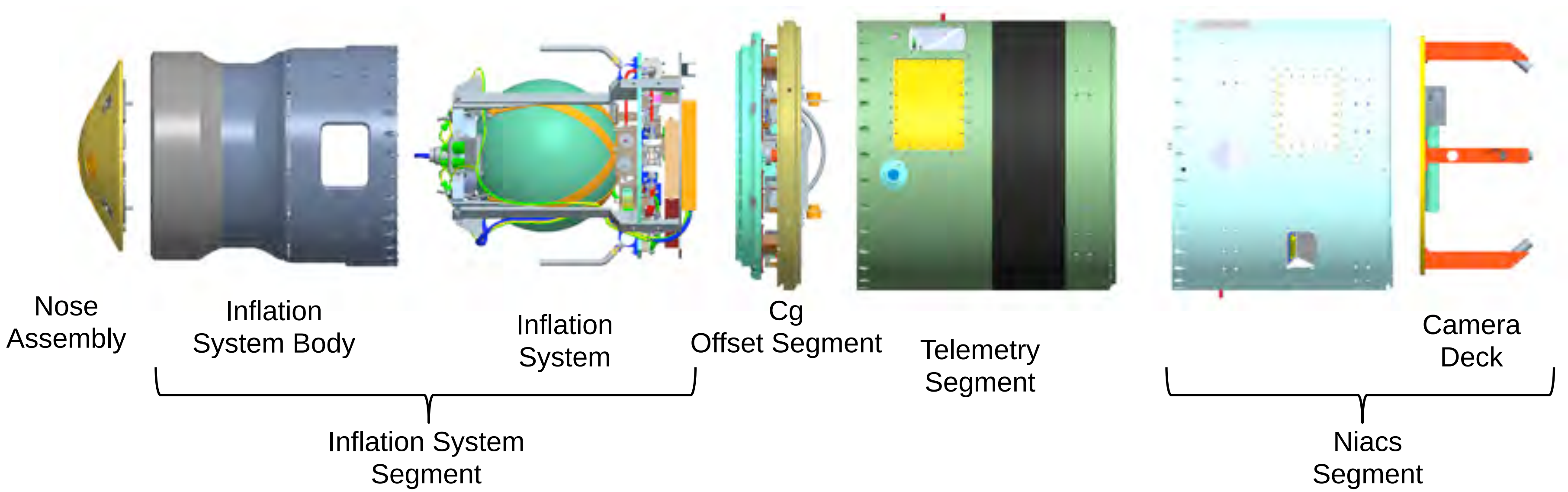
- **RV hardware fabrication complete**
- **RV Assembly**
  - Inflation System Segment subassemblies complete
  - CG Offset Segment mechanical subassemblies complete
  - TM Segment assembly complete, with antenna installation on standby
  - NIACS Segment assembly complete, with gyro installation on standby
  - Nose and camera deck assemblies in process
- **Avionics**
  - Began updating and reorganizing engineering data from lessons learned on IRVE-3
  - Began checkout and calibration of avionics boxes



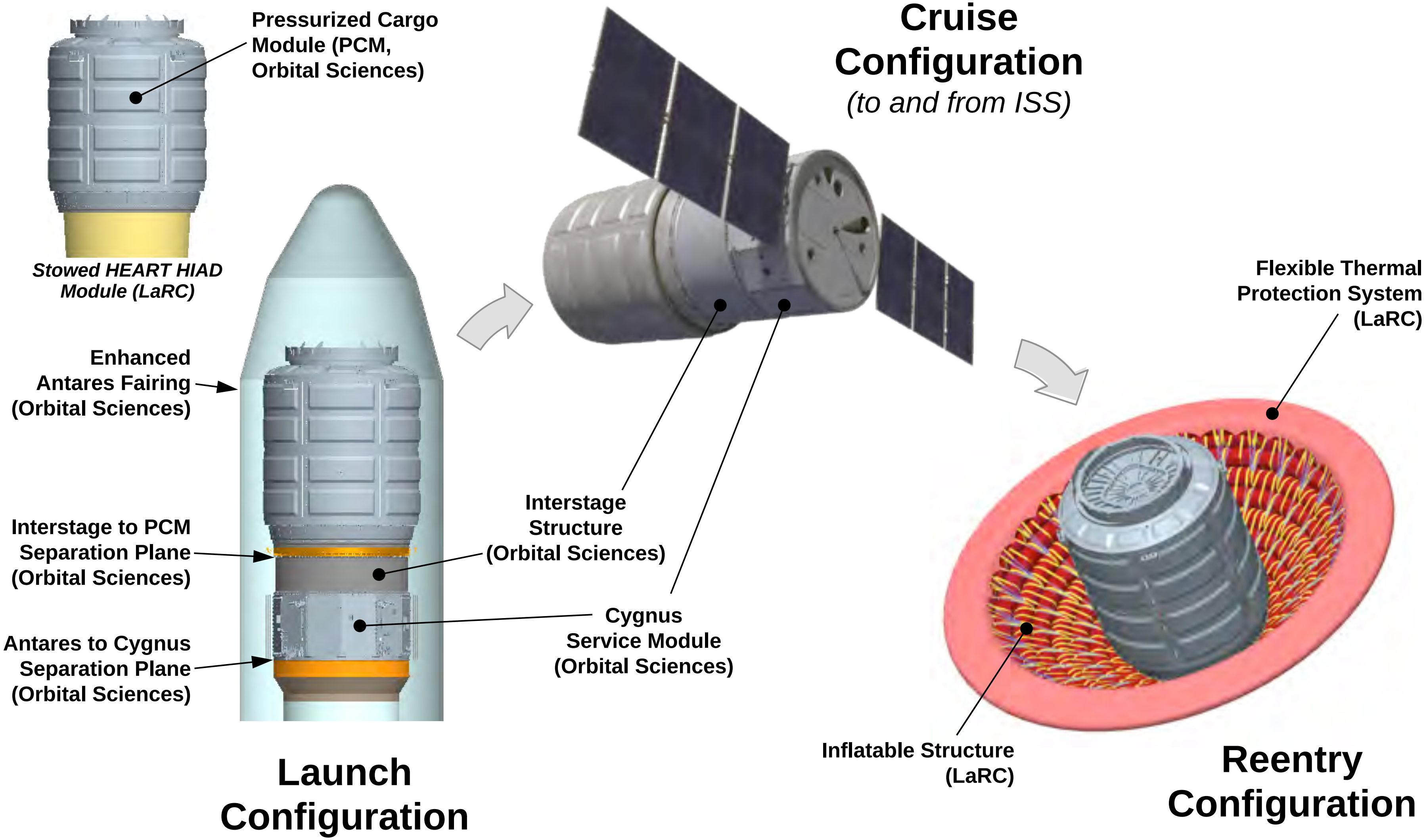
IRVE-4 Inflation System (ready for avionics integration)

IRVE-4 Upcoming Work

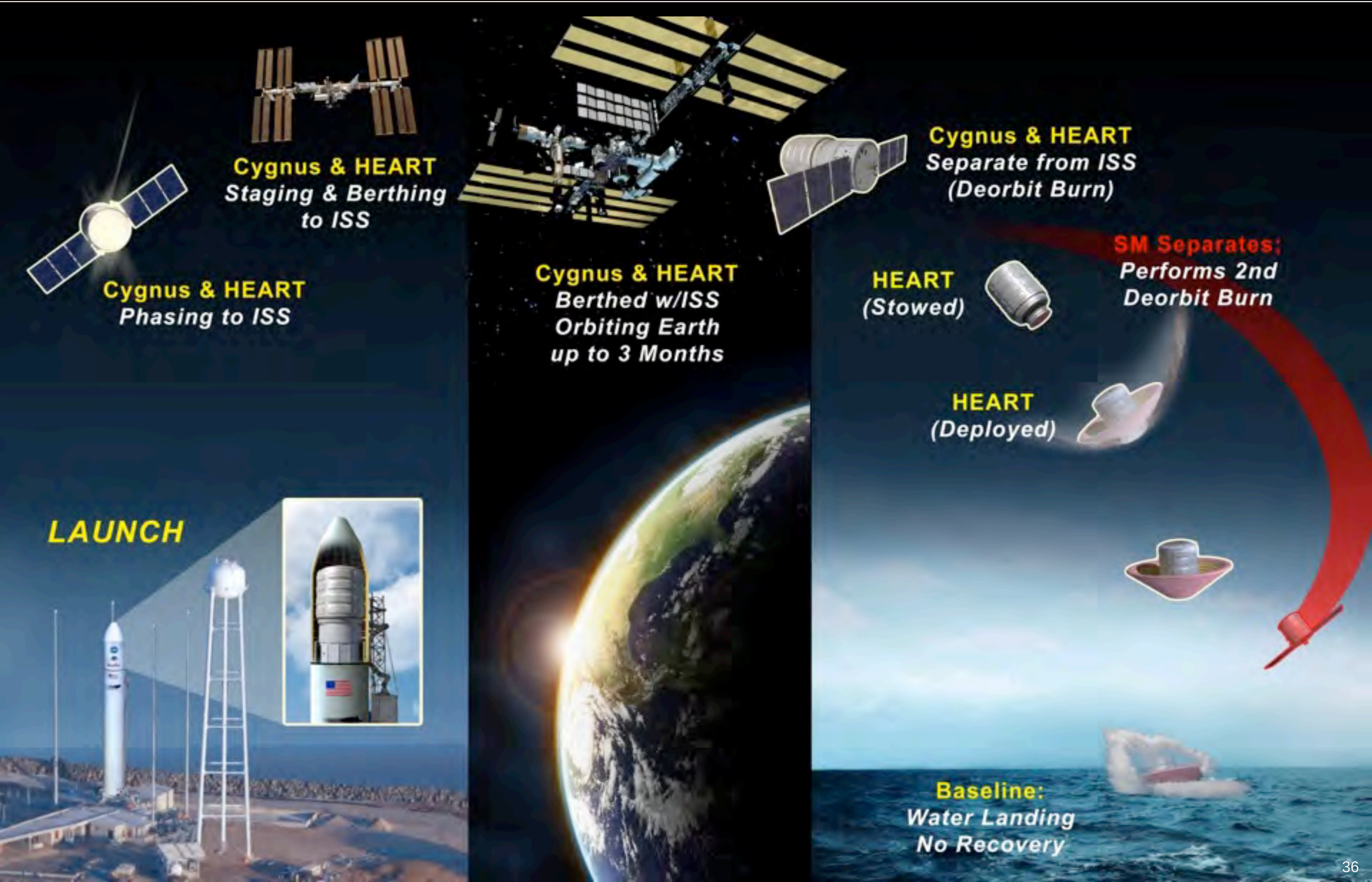
- **Complete engineering data packages and checkout of Avionics**
- **Perform fit check of Nose Assembly (excluding TPS), Inflation System Segment, and CG Offset Segment with Avionics components and initial wire harness routing**
- **Complete functional testing and finalize flight integration of Avionics with Inflation System and CG Offset Segments**
- **Perform workmanship vibe testing of Inflation System and CG Offset**



The HEART Concept



HEART Concept of Operations

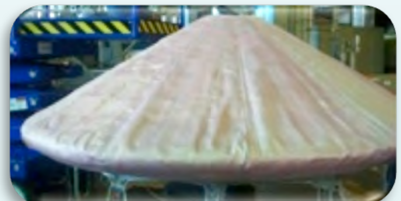


Technology Maturation from the HIAD Project

HEART Baseline TPS and Inflatable Structure are directly derived from the IRVE-3 Flight Test and HIAD Ground Developments

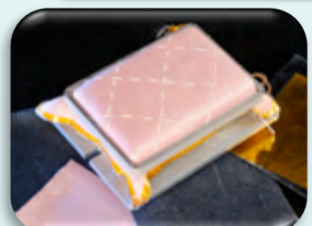
Integrated Demonstration Flight Test – IRVE-3

TPS

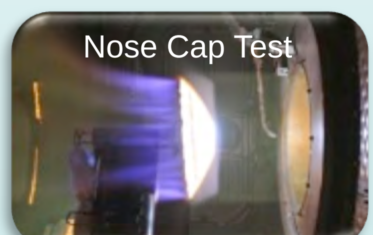


TPS EDU for 6 m IAD – 2012/2013

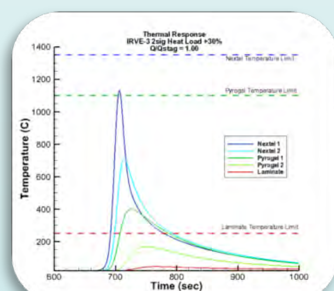
Catalycity Testing UVM – 2011



Shear Testing LCAT – 2011/2012



Stagnation Testing TP2 – 2011

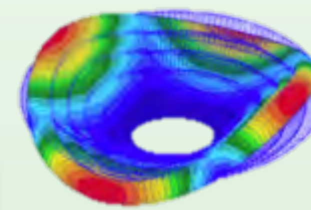


TPS Modeling

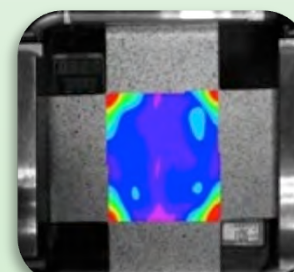
Inflatable Structure

Static Load Test 3m Dia FY11 & FY12

Aero Load & Deflection Test 6 m Dia (NFAC-2012)



Structural Modeling



IS mat'l prop. characterization

HIAD Future Plans & Challenges

- **FY13 Plans:**
  - Complete the fabrication of the 6-m TPS
  - Complete the fabrication of the 6-m Inflatable Article
  - Complete the HTT TPS Aeroelastic Flutter Tests
  - Complete FY13 LCAT testing
  - Complete FY13 LAL testing
  - Continue Thermal and Structural Model Designs
  - Deliver 21 Technical papers and 6 Conferences

- **Challenges**
  - Converting workforce from WYE to CS
  - Lack of procurement funds